REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 2000	3. REPORT TYPE AND DATES COVERED Article

4. TITLE AND SUBTITLE

Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics 2000

5. FUNDING NUMBERS

6. AUTHOR(S)

Dr. Arthur J. Mariano, Dr. Annalisa Griffa, Dr. Tamay M. Ozgokmen, Dr. Enrico Zambianchi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics (LAPCOD)

8. Performing Organization Report Number

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

Office of Naval Research, Ballston Centre Tower, 800 North Quincy Street Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

ABSTRACT (Maximum 200 words)

The first Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics (LAPCOD) meeting took place in ISCHIA, Italy from Oct. 2-6, 2000. The material presented at LAPCOD 2000 indicated both a maturing of Lagrangian-based observing systems and the development of new analysis and assimilation techniques for Lagrangian data. This study presents a review of the state-of-the-art technology in Lagrangian exploration of oceanic and coastal waters..

14. SUBJECT TERMS

ONR, Research, Observational results, Model-data comparison, Lagrangian simulations, Predictability, Assimilation, Lagrangian data

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics 2000

by

Dr. Arthur J. Mariano, University of Miami, Miami, FL, USA

Dr. Annalisa Griffa, University of Miami, Miami, FL, USA

Consiglio Nazionale (CNR)/ IOF, La Spezia,Italy

Dr. Tamay M. Özgökmen, University of Miami, Miami, FL, USA

Dr. Enrico Zambianchi, Istituto Universitario Navale, Naples, Italy

AQ F03-11-2467

Abstract

The first Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics (LAPCOD) meeting took place in Ischia, Italy from Oct. 2-6, 2000. The material presented at LAPCOD 2000 indicated both a maturing of Lagrangian-based observing systems and the development of new analysis and assimilation techniques for Lagrangian data. This study presents a review of the state-of-the-art technology in Lagrangian exploration of oceanic and coastal waters.

1 Introduction

It is an exciting time to be studying fluid motion from a Lagrangian perspective because of maturing observation techniques, new sensor technology and analysis methods, and increased computational power for numerical simulations. Multi-disciplinary research involving biologists, physical oceanographers, mathematicians and engineers is synergistically improving our understanding of chaotic advection, turbulent mixing, and nonlinear particle dynamics in biological and physical systems. In order to further accelerate this research, the first Lagrangian Analysis and Predictability of Coastal and Ocean Dynamics (LAPCOD) meeting took place in Ischia, Italy from Oct. 2-6, 2000 (see www.rsmas.miami.edu/LAPCOD). This paper is a review of the observational and theoretical results from LAPCOD 2000, as well as a summary of recommendations for future Lagrangian-based exploration of the biology and physics of oceanic and coastal waters.

2 Observational results

Lagrangian data are primarily used by oceanographers for estimating the climatological mean flow of the ocean and its marginal seas, and for the information that Lagrangian data can provide on the basic statistics of subgrid-scale velocity and dispersion. New data sets that span a vast range of geographical locations and instrument design (*e.g.* subsurface floats, different types of surface drifters and High Frequency (HF) radar) observe phenomena at basin scale, important for climatic studies, to small-scale coastal observations targeted for environmental applications. Results for (near-)surface circulation in the tropical Pacific, in the Caribbean and in two subbasins of the Mediterranean Sea, the Adriatic Sea and Balearic Sea, are presented next, followed by observations from subsurface RAFOS floats in the Northeast Atlantic ocean.

A new methodology for mean-flow eddy decomposition (Bauer *et al.*, 1998) was used to estimate seasonal maps of eddy diffusivity from near-surface buoys in the tropical Pacific. Time-dependent mean flows are estimated by fitting, to each horizontal velocity component, a least-squares smoothing bi-cubic spline to bimonthly groupings of the data. The resulting residual mesoscale velocity is modelled as an Auto-Regressive (AR) process (see below) and diffusivity estimates are derived from the parameters of an AR model. Zonal diffusivity estimates, 5-76 $\times 10^7 cm^2/s$, are, in general, larger than meridional estimates, 2-9 $\times 10^7 cm^2/s$. Larger values are found in regions of strong meridional shear between the North Equatorial (NE) Current and the

NE counter-current. (AR) models of order 1 (2) are appropriate for all zonal velocities and for weak (strong) meridional velocities. Lagrangian integral time scales are on the order of 2-3 days.

Seasonal maps of mean velocity in the Adriatic Sea, calculated from over 200 satellite-tracked drifters from 1990-1999, show three distinct recirculation cells in the northern, central, and southern sub-basins (Poulain, 1999; 2001). Mean velocities in the cyclonic gyres can exceed 25 cm/s with maximum velocity variances exceeding 500 cm^2/s^2. Along-isobath diffusivity is 2 $\times 10^7 cm^2/s$, with integral space and time scales of 18 km and 2 days, respectively. Cross-isobath diffusivity and spatio-temporal scales are approximately one-half of along-isobath estimates. Plots of mean kinetic energy and eddy kinetic energy vary as a function of bin size used to calculate the mean flow and autocovariance function, a result widely reported by others. A bin size where both of these quantities saturate and are robust is required for good estimates of Lagrangian velocity statistics. Polauin (2001) used overlapping 40 km circular bins.

Approximately 100 near-surface buoys were launched in the Caribbean Sea during the last few years as part of the NOPP "Year of the Ocean" project (Wilson and Leaman, 2001). There is a broad westward flow in the northern and eastern parts of the Caribbean basin, and a considerable number of both cyclonic and anti-cyclonic eddies exist. The flow in the southwest Caribbean is dominated by the quasi-permanent gyre known as the Panama-Colombia gyre. Drifters launched in this gyre have retention times of a few months, and one preferential pathway ends in the shelf waters off southern Cuba.

Bower *et al.* (2001) reviewed results of 44 RAFOS float observations at 1000 m depth near and off-shore of the Iberian peninsula. The float trajectories revealed 4 meddies near Cape Saint-Vincent, implying a formation rate of 15-20 meddies/year. These anti-cyclonic eddies take 3-7 days to form, have a velocity integral time scale of 3-4 days, and influence the path of the Mediterrean Undercurrent. The mean background flow was 15-20 cm/s with peak velocities of 40 cm/s. On the other side of the Iberian peninsula, in the Northwestern Mediterranean, near-surface float observations in the Catalan current in June 2000 measured a 30-40 cm/s flow. The Catalan current primarily flows along the continental topography as it advects low salinity water and fish larvae from the Gulf of Lions to the open sea (Sabatis *et al.*, 2001). The floats also exhibited strong inertial oscillations after the passage of a storm.

Bezerra *et al.* (1998) used velocity measurements from buoys and video imaging techniques to estimate dispersion in the coastal waters of Spain and Brazil as a function of wind stress, wave height, strength of tidal currents, and distance from shore. Milk was used as the tracer for the

imaging techniques. Horizontal diffusivity values ranged from $1 cm^2/s$ to $2 \times 10^4 cm^2/s$ and were a strong function of the Wave Reynolds number and the wind stress. Anisotropy increased near the coast, presumably due to the long-shore currents.

115 isopycnal ($\sigma_\theta = 27.5$) RAFOS floats were deployed by Rossby and colleagues in the subpolar fronts in two primary regions: just west of the mid-Atlantic ridge and along the eastern margin of the North Atlantic. These float trajectories appear to have preferred pathways, indicating a strong influence from topography, especially when stratification is weak and sub-mesoscale/mesoscale mixing is strong. The mean flow is eastward through the Charlie Gibbs Fracture Zone, and there are two primary northward pathways: (i) northeast into the northern Iceland basin west of the Rockall/Hatton bank, then southwest along the Reykjanes Ridge, and then northward into the Irminger Sea; or (ii) abruptly to the northwest towards the Reykjanes Ridge.

Zhang *et al.* (2001) calculated an average Lagrangian integral time scale of 2 days for RAFOS floats in the N. Atlantic Current and 3.2 days for floats in the Newfoundland Basin. These floats nominally sampled σ_θ 27.2 and 27.5 surfaces. Diffusivity values ranged from 1 to $7 \times 10^7 cm^2/s$ and space scales ranged from 20 to 30 km. These estimates are sensitive to the horizontal bin size used for calculating the mean flow and autocovariance functions. Since observations from over 100 floats were available, $1/2°$ by $1/2°$ horizontal bins had sufficient data to resolve the heterogeneous flow field with large mean velocity shear.

Residual velocity statistics for these floats are approximately Gaussian only after the mean velocity shear is properly removed. The dispersion of the residual velocities follows Taylor's (1921) well-known result; that is, diffusivity grows linearly with time initially after launch, and for large time, it is proportional to the Lagrangian integral time scale T_L (the velocity variance is the constant in both cases). RAFOS floats have integral time scales on the order of 1 day when isopycnals shoal, and deeper subtropical floats have time scales as long as 11.5 days. For comparison, SOFAR floats in the main and lower thermocline of the N. Atlantic have time scales on the order of a week to two weeks (Rossby *et al.*, 1983).

Very interesting results for the surface circulation in limited domains can be obtained by combining Eulerian data with Lagrangian analysis. Results from high horizontal and temporal (250 m and 20 min) resolution OSCR surface velocity data from the 4-D current experiment in the coastal region off Hollywood, FL during the summer of 1999 indicate significant dynamical events including submesoscale vortices, large lateral meandering of the Florida Current on time

4

scales of hours, eddy mergers and periods of strong anomalous southward flow. Dominant periods are 27 hrs (inertial), 10 hrs (associated with a vorticity wave), and a few days (Florida Current meandering). Dominant spatial scales of the eddies are on the order of 2-3 km, with peak propagation speeds of 30-40 cm/s northward (Shay et al., 2000; Peters et al., 2001). Simulated trajectories "launched" at the latitude of the Broward County Sewage Outfall suggested beaching of particles became more evident for particles launched within 2 km of the coast, and that most particles launched 4 km or more off-shore exited the area.

Results from HF radar maps of surface currents in Monterey Bay reveal a flow field that consists of background and geostrophic currents, upwelling-induced currents, and sea-breeze driven and tidal currents. These velocity data are used to simulate particle trajectories and as input into a dynamical system analysis. Both simulated particle trajectories and the dynamical system analysis indicate two distinct regimes for residence times of near-shore particles. Particles launched near-shore either exit Monterey Bay within five days or recirculate in the bay for weeks (Kirwin, pers. com.). The areal extent and center point of these regimes change on time scales of a few hours (Coulliette et al., 2001).

HF velocity data can be projected onto GOFs, Geometrical Orthogonal Functions, that consist of vorticity basis (equal to streamfunction for zero-divergence) and a divergence basis that is like the velocity potential (Lipphardt et al., 2000). GOFs calculated for HF data in Monterey Bay from the years 1994 and 1999 were not significantly different. Spectra of the modes reveal peaks at one and two cycles per day as a result of tides and wind-forcing. Significant low-frequency energy also exists in vorticity modes associated with large-scale transport.

Inspection of trajectories from the Lagrangian data archives reveals that the descriptive character of Lagrangian trajectories in the ocean exhibits classical examples of both standard and non-standard dispersion behaviors, most likely determined by the joint effects of turbulent diffusion and chaotic advection. A number of float clusters have either remained coherent for thousands of kms and many months, or rapidly dispersed and sampled vastly different parts of the oceans even though they were launched "close" together. There are also trajectories from floats that were launched far apart and then almost touched each other, as well as float trajectories that are text-book examples of time-averaged general circulation of the ocean and of potential vorticity conservation (see Fig. 1 and 2; Rossby et al., 1983; Mariano and Rossby, 1989; Garfield et al., 2001).

5

3 Biological studies

The Lagrangian approach is not too widespread in the biological oceanographic community, even though it is probably the most natural one, since the emphasis is on organisms whose motion in many cases can be considered at least partly coincident with the Lagrangian circulation. One of the reasons may well lie in the fact that the forcing results from the combination of biological and dynamical phenomena, and this often calls for the implementation of hybrid description and simulation techniques, i.e. partly Lagrangian and partly Eulerian, which brings strong conceptual and technical difficulties. There are great possibilities for this approach, anticipated in the recent works by Hitchcock *et al.* (1997), Ye and Garvine (1998), Polivina *et al.* (1999), and Wolanski *et al.* (1997). However, there is still room for further improvements. Transport and dispersion of fish larvae and phytoplankton, for example, are especially well-suited for a Lagrangian-based analysis.

There is a debate about the degree of teleconnections between remote populations of fish in the Caribbean Sea. A key component needed to settle this debate is the dispersion rate of the fish larvae in the open sea and near the coast. Early models based on mean-flow advection and eddy dispersion, as well as genetic evidence, suggest that long distance dispersal of larvae is likely a common event leading to considerable teleconnections among distant populations. However, new results (Cowen *et al.*, 2000) demonstrate that local retention is more the rule and that long distance transport is likely insufficient, due to mortality, to sustain marine populations ecologically. Numerical model simulations and *in-situ* data near Barbados support the hypothesis that coral fish larvae capitalize on flow structure to be retained in the proximity of their native island. Behavorial aspects of marine population must also be modeled as close to reality as possible.

Numerical investigations of the vertical distribution of phytoplankton require simulating the behavior of phytoplankton cells using a biological model coupled to an advection-diffusion transport model. D'alcala's model includes turbulent mixed layer vertical velocities and eddy dispersion, a time and depth dependent light source for cell growth, nonlinear growth/irradiance relationship, self-shading effect, photoadaptation processes, and different scenarios for available nutrients. When the probability of finding sufficient nutrients is low ($< 1/3$), the plankton are homogeneously distributed throughout the water column. As this probability increases (>0.5), plankton patchiness increases, and for high probability of finding nutrients (.95), the plankton

are randomly distributed.

Bracco (*et al.*, 2000c) point out that *in-situ* observations contain a much larger number of plankton species than predicted by the competitive exclusion principle, which limits the number of species by the number of resources, the so-called paradox of the plankton problem. Solutions obtained by coupling a stochastic particle model (either a random walk or random flight) and competitive plankton models to simulations of barotropic turbulence show that less-fit plankton can be protected from competition while trapped in vortices. These transport barriers allow the co-existence of more competitive species than predicted by the competitive exclusion principle (Bracco *et al.*, 2000c).

4   Model-data comparisons and Lagrangian simulations

The number of investigations comparing results from Lagrangian data to results of different general and regional circulation models are increasing. Along with the traditional goal of such studies, namely the validation and improvement of the models, model results can be used to study properties of Lagrangian statistics and can be used to get insight into the relationships between Eulerian and Lagrangian velocity statistics. In addition to these more traditional applications, results from studies directed at a true Lagrangian utilization of numerical results, *i.e.* the tracing of water masses and of particle and biogeochemical property exchange in the framework of realistic simulations of three-dimensional coastal and ocean circulation, are now approaching a more mature science.

A comparison has been performed between simulated mixed layer drifters from MICOM (Miami Isopycnal Coordinate Ocean Model) and the near-surface drifters archived at Atlantic Oceanographic and Meterological Laboratory (AOML) for the North and tropical Atlantic ocean. MICOM was forced by climatological winds for 20 yrs after Levitus initialization and was configured with 16 layers and a horizontal resolution of 1/12°. Two years after launch, the simulated particle density exhibited the well-known Ekman convergences and divergences. Pseudo- Eulerian mean velocity fields calculated from model trajectories and from *in-situ* drifters, in general, showed good agreement. Problem areas were near the boundary of the model domain and near strong currents due to the model having the Gulf Stream, for example, a little too far north. The Lagrangian integral time scales were over-estimated in the model by a factor of two. This is presumably due to using relatively smooth climatological winds to force the model (Garraffo *et*

al., 2001a).

Float-model comparisons have also been performed using the North Atlantic World Ocean Circulation Experiment surface drifters and simulated trajectories from both a 0.1° and a 0.28° horizontal resolution, 40 vertical level North Atlantic configuration of the Los Alamos National Laboratory Parallel Ocean Program (POP) model forced with 1993-1997 Navy Operational Global Atmospheric Prediction System (NOGAPS) daily winds. The mean pseudo-Eulerian velocity statistics and estimates of the Lagrangian integral time scales from the simulation with 0.1° horizontal resolution were closer to *in-situ* estimates than the 0.28° simulation. The coarser resolution simulation tended to over-estimate the integral time scales (McClean *et al.*, 2001).

A problem by which both of these model-data comparisons were hampered is the lack of *in-situ* data, especially in the tropical Atlantic. Garraffo *et al.* (2001b) used the same MICOM surface velocity data as Garraffo *et al.* (2001a) and showed that the largest error source in calculating mean Eulerian velocity fields from Lagrangian data is due to sampling error. Bias errors (see Davis, 1991) are also significant, due mostly to to preferential sampling in divergent regions. Sampling error is a function of the finite data size and the variability associated with the unresolved flow scales. It will take a large number of *in-situ* data to produce global maps of the climatological mean circulation because of the energetic and broad spectrum of sub- and mesoscale motions.

Garfield *et al.* (2001) compared simulated drifter trajectories from 0.28° horizontal resolution Parallel Ocean Program model simulations and 38 isobaric RAFOS floats in and near the California Undercurrent. Both *in-situ* and simulated trajectories show the poleward flowing California undercurrent, a weak flow west of the undercurrent, and a strong westward-propagating eddy field that enhances the mixing between near-coastal water and the deep ocean. The model underestimated the mean flow and eddy kinetic energy level in this area presumably due to coarse resolution.

Simulated trajectories from a two-dimensional shallow water model and trajectories from visualized particles in the 14 m diameter "Coriolis" rotating tank of the LEGI-IMG located at Grenoble (France) were compared. Experiments were conducted over a range of water depths, rotation rates, and the spacing and speed of the grid used for stirring the fluid. The flow in these experiments, which span a range of (initial) Rossby numbers between 0.3 and 4.6 and Reynolds numbers between 10^3 and 10^4, is dominated by coherent vortices that trap fluid particles and are impermeable to inward particle fluxes. There was good agreement between the statistical

properties of the numerical and visualized trajectories (Longhetto *et al.*, 2001).

Rolinski analyzed the results of a three-dimensional Lagrangian model (see Rolinski and Suendermann, 2001a) for the transport, deposition, and resuspension of Suspended Particulate Material (SPM) applied to the River Elbe in Germany. She compared different approaches for estimating the residual Lagrangian velocity from the baroclinic velocity field and used these residual velocities to study why SPM accumulate in freshwater regions in the estuary. Transport by coherent eddies is a dominant physical mechanism. She also discussed coupling this Lagrangian model to a finite element model of Venice Lagoon (Rolinski and Suendermann, 2001b). Difficulties include conversion of current fields from a finite element circulation model onto a Lagrangian model that uses finite differences in a domain whose wet/dry boundaries change rapidly. Special care must be used to set up volume-conserving equivalent elements based on complicated bathymetry and the amount of "wet" vrs "dry" areas. It is important to conserve volume to reduce accumulation errors in the smallest grid volumes.

SPM simulations for the Thermaikos Gulf in Greece were compared as a function of different assumptions for vertical particle motion. Daily average velocities from a POM (Princeton Ocean Model) simulation were used to advect particles; vertical movement was controlled by the local vertical velocity and the particle settling velocity; turbulent diffusion was modeled as a Brownian process; and SPM processes such as resuspension, settling, and flocculation were also included in the model. 30,000 particles were tracked, and their average settling rate was 0.5 to 1.0 mm/yr. SPM processes lead to particles sinking faster than those predicted using just the local vertical velocities from the model (Koutitas, pers. com.).

TRACMASS (TRACing the Water MASSes) is an off-line code used to track water parcels that was applied to the output of a numerical simulation of the Mediterranean Sea. TRACMASS is fast, accurate, and able to track particles in three-dimensions. 100,000 parcels, for example, were launched at the straits of Gibraltar at 50 m depth and tracked for hundreds of years. The mean arrival time for these particles were then calculated and mapped for the entire Mediterranean Sea. On time scales of a year, particles were advected along the North African Coast. On time scales of decades, particles reached the eastern Mediterranean and filled out the basin. Particles reach the Adriatic Sea and Northern Ionian Basin on time scales of a hundred years presumably due to the production of Levantine water that lead to relatively younger water sinking and changing its flow direction (Rupolo, pers. com.)

5   Applications of stochastic models

Stochastic models are used to study particle statistics in the ocean. In particular, non-Gaussian properties seen in the Probability Density Functions (PDF) of Lagrangian velocities can be modelled using stochastic models with a small number of parameters, and their implications in terms of model structure and dispersion properties can be investigated. In general, stochastic models for Lagrangian particle trajectories in the ocean perform best at intermediate temporal lags. At small temporal lags, flow statistics are highly dependent on the flow conditions at the initial launch location, while at large temporal lags, boundary effects and the effects of potential vorticity constraints become dominant. Ironically, theoretical models for Lagrangian flow statistics are most easily derived for small time and for large time after launch.

Thompson (1986) formulated a random flight model for particle dispersion that is based on an Auto-Regressive model of order one, $AR(1)$ or equivalently known as a Markov process, for turbulent velocities. The Markov random flight model differs from the random walk model by including a correlated velocity component that, in most applications, models the turbulent mesoscale. Thompson (1987) showed that the Lagrangian PDF for one-particle velocity statistics is related to the Eulerian PDF for the fluid velocity since they both satisfy the same Fokker-Plank equation. Consequently, models of the Eulerian velocity PDFs are directly applicable to models of turbulent dispersion (e.g. Maurizi and Tampieri, 1999).

The use of this model and parameter estimation for oceanic data is reviewed by Griffa (1996). This model has been used successfully in a number of applications such as predicting Lagrangian motion (Falco *et al.*, 2000) and modeling dispersion in near-surface drifting buoys (Bauer *et al.*, 1998), but in all these studies, the limitations of this model are clearly seen. $AR(2)$ and $AR(3)$ models are now being evaluated by Berloff *et al.* (2001a; 2001b) and Pasquero *et al.* (2001). $AR(2)$ models are needed when there is a strong looping motion or wave motion seen in particle trajectories. $AR(3)$ models are needed when the velocity field has long-time memory that can result from being trapped in a vortex. It is usually assumed that the velocity components are independent and each is of the form,

$$dx = (U(x, y, t) + u(x, y, t))dt$$

$$du = \frac{-u}{T_L}dt + \sqrt{\frac{2\sigma^2}{T_L}}d\eta,$$

where U is the mean flow, u is the turbulent velocity component modeled as an $AR(1)$ process,

10

σ^2 is the variance of the $AR(1)$ (or Markov) process, T_L is the Lagrangian integral time scale $(T_L = \int_o^\infty C(\tau)d\tau)$, and $d\eta$ is a white noise process. The velocity autocovariance function, $C(\tau)$, expotentially decays to zero with $C(2T_L) \approx 0$. Particle dispersion initially grows quadratically with time and then asymptotes to a linear function of time. The $AR(1)$ model generalizes to an $AR(2)$ model by also assuming that the particle acceleration, a, can be modeled as a Markov process with an integral time scale of T_a,

$$dx = (U(x,y,t) + u(x,y,t))dt$$

$$du = \frac{-u}{T_a T_L}dt - (\frac{1}{T_a} + \frac{a}{T_L})dt + (\frac{\sigma^2}{T_a}(1 + \frac{T_a}{T_L}))^{1/2}d\eta.$$

The Lagrangian velocity autocorrelation function has two time scales, and if $T_a > T_L$, the correlation can become negative.

If the Probability Density Function (PDF) of Lagrangian velocities was truly multi-variate Gaussian and homogeneous in the ocean, then theoretical estimates of dispersion statistics would be exact and we could derive, for example, a set of equations for an Extended Kalman Filter for assimilation of data into ocean circulation models that would be closed. However, at best, ocean statistics are only approximately Gaussian, and they are most definitely heterogeneous in space and nonstationary in time. Calculated PDFs, from *in-situ* float data or from simulated trajectories from large eddy simulations of geostrophic turbulence and ocean circulation models, differ the most in the tails of their distribution from a true Gaussian distribution. Put simply, turbulent ocean flow is approximately Gaussian with more extreme values. Numerical and experimental results illustrating non-Gaussian PDFs are now performed at better resolutions because of the ever-increasing computational power that is becoming available to researchers at lower and lower costs. In particular, Maurizi and Lorenzani (2000) analyzed experimental data from wall and shear-generated turbulence and suggested that the kurtosis, K, of the Eulerian velocity PDF is related to the Skewness, S, by $K = c(S^2 + 1)$, where c is estimated to be in the range of of 2.3 to 2.5.

It is now well-known that coherent vortices can introduce far-field correlations that can not be modeled using Gaussian statistics (McWilliams, 1984; Weiss and Mc Williams, 1993 ; Bracco *et al.* 2000a,b). Pasquero *et al.* (2000) investigated the behavior of an $AR(1)$ stochastic particle model and a two-component stochastic model in a numerical simulation of forced barotropic turbulence on a doubly-periodic 512 x 512 grid. The two component model decomposes the velocity field into a background and a vortex component and each component is modeled as an $AR(1)$ process. This

model is further improved by incorporating non-Gaussian behavior into the $AR(1)$ model for the vortex component by allowing the AR coefficient to be a nonlinear function of the background velocity. They show that the dispersion statistics derived using an $AR(1)$ model can be off by as much as 25%, mostly at intermediate lags, and that exit times are under-estimated and are a strong function of higher-order moments. Their nonlinear stochastic model significantly improved the exit time estimates.

Material spreading and mixing by oceanic mesoscale eddies are analyzed in an idealized, numerical model of the wind-driven, mid-latitude oceanic circulation (Berloff *et al.*, 2001). The analyses are based on ensembles of Lagrangian particle trajectories. It is shown that tracer transport by mesoscale eddies differs in many ways from the commonly used model of homogeneous, isotropic eddy diffusion. The results suggest reconsidering the traditional diffusion approach. A hierarchy of inhomogeneous, non-stationary stochastic models of material transport is formulated, and its properties are described by Berloff and McWilliams (2001). The transport models from the hierarchy sequence provide progressively more skillful simulations of the subgrid-scale transport by mesoscale eddies, which are typically not resolved in coarse-grid representations of the ocean circulation. Performance of the models is evaluated by (a) estimating their parameters from Eulerian and Lagrangian statistics of a fluid-dynamic reference solution, (b) solving for the transport, and (c) comparing the stochastic and direct fluid-dynamic transports.

Numerical results from these and other simulations and some observational evidence suggests that single-particle disperson statistics are not linear in time at intermediate lags as suggested by Taylor (1921). Sub-diffusion results when particles are trapped by vortices and planetary waves, while super-diffusion can be found in western boundary regions. Sub-diffusion leads to negative lobes in the velocity autocorrelation function, while super-diffusion leads to enhanced positive correlations. $AR(2)$ models are a big improvement over $AR(1)$ models, especially in deep layers that exhibit "oscillatory" velocity correlation functions. $AR(3)$ stochastic models are needed for super-diffusive flows when mean advection dominates.

Buffoni (pers. com.) analyzed the dispersion properties of particle in a semi-enclosed basin by assuming no particle interactions and the probability of finding a particle in the basin is the same for all particles. Under these assumptions the number of particles in the basin at any instance of time has a binomial distribution. Even though these assumptions could easily be questioned, numerical simulations with various flows are able to reproduce the theoretical estimates of mean residence times and their variance.

6   Nonlinear dynamics and dynamical system theory

There is a one-to-one correspondence between the phase space of dynamical system analysis and the physical space of a two-dimension fluid. This correspondence can be exploited to relate mathematical phenomena such as KAM tori, chaos, and invariant manifolds to physical phenomena such as fluid transport barriers, efficient stirring, and mixing of fluids and the geometry of particle trajectories, respectively (Babiano *et al.*, 1994; Wiggins, 1992). Recent techniques have focused on identifying hyperbolic stagnation points, defined by the intersection of a stable manifold (fluid particles are attracted toward the hyperbolic point) and unstable manifolds (particles are repelled away from hyperbolic point) from a nonlinear analysis of the critical points of a velocity field. Lobe dynamics (Malhotra and Wiggins, 1998) identify the most important intersection of stable and unstable manifolds, basically moving saddle points known as hyperbolic trajectories that divide the flow into distinct regimes. The rate of fluid mixing can be calculated as a function of the area of the lobes.

It is extremely challenging to detect hyperbolic trajectories in large, model-generated velocity fields or oceanographic data that are, in general, finite in time, aperiodic, noisy, three-dimensional in space, gappy, and may have open boundaries. Methods are being developed to overcome each of these difficulties (Wiggins, 1992, Coulliette and Wiggins, 2000; Malhotra and Wiggins, 1998; Haller and Poje, 1998; Haller, 2000; Miller *et al.*, 1997). Efficient methods for finding the *distinguished hyperbolic trajectories* for large, time-dependent sets are discussed in Ide *et al.* (2001), Lekein (pers. com.) and Kuznetsov *et al.*, 2001). These methods define the Distinguished Hyperbolic Trajectories (DHTs) (or equivalent) based on frozen-time/instantaneous stagnation points and zero velocity curves. DHTs divide the flow field into different regimes with similar properties such as residence time of particles.

Ide applied her analysis to velocity fields from a classic, wind-driven double-gyre ocean model simulation. The Eulerian transport is defined as the net amount of fluid particles and properties that migrate from one region to another across a stationary boundary over a time interval. Ide defined the stationary boundary by a reference streamline determined by a nonlinear analysis and defined as the DHTs. Efficient algorithms for identifying DHTs in large, model-generated data sets are detailed in Ide *et al.* (2001).

Lekien analyzed the inter-gyre exchange from a 3 layer QG double-gyre model simulation in a $(2000\ km)^2$ domain. He showed that DHTs and stagnation points can be as far apart as

300 km. This justifies the need for an accurate method to compute those DHTs, even though the associated computational load is considerable. The inter-gyre transport was shown to be a function of the lobes that define the intersection of the stable and unstable manifold of the DHTs.

Kuznetsov *et al.* (2001) analyzed Gulf of Mexico simulations from the POM model. Effective Invariant Manifolds (EIMs) can be computed from "noisy" model fields and be used to identify flow structure. EIMs are distinct regions in the fluid flow with similar properties. This analysis quantified the exchange of water between an anti-cyclonic Loop Current warm-core ring and a small cyclonic eddy and provided a detailed history of ring formation. The analysis showed that cyclonic rings have enhanced mixing regions along their boundary and that the larger anti-cyclonic rings were relatively isolated (see Fig. 2).

Dispersion and mixing can also be studied using tools from nonlinear dynamical systems theory. Vulpiani (pers. com.) pointed out that asymptotic estimates of tracer dispersion are not possible in small domains where the dominant Eulerian length scale is not much smaller than domain size because of boundary effects. Vulpiani used Finite Scale Lyapunov Exponents (FSLEs) to estimate that one-particle dispersion can grow as t^3 in simple chaotic flows. FSLEs, $L(R)$, are a generalization of Lyapunov Exponents (LEs), L, that are a function of the separation distance between particles, R, and they are used to quantify dispersion. In the limit of R approaching zero, $L(R) = L$. When L is positive the fluid undergoes chaotic mixing. When R is less than the domain size, $Rmax$, $L(R)$ scales as D/R^2, (velocity variance approximately equals $4Dt$ at time t), and for R approximately $Rmax$, $L(R)$ scales as $\frac{(Rmax-R)}{R}$, where the coefficient is the inverse of the relaxation time to uniform particle distribution.

FSLEs were used to analyze the dispersion of simulated trajectories in an ocean general circulation model of the Mediterranean Sea. Spatial maps of FSLEs indicated regions with strong turbulent mixing, as well as regions with weak mixing. Relative dispersion was dominated by mean shear effects up to gyre-scales and by mesoscale chaotic advection. FSLEs were also used to analyze tracked Lagrangian particles from an essentially two-dimensional convection experiment that exhibited strong chaotic motion at large Rayleigh number ($Ra \propto O(10^8)$). The Lagrangian motion was found to be chaotic with a Lyapunov exponent that scales with the Rayleigh number as $Ra^{1/2}$ (Boffetta *et al.*, 1999; 2000).

Abel *et al.* (2001) used Bower's (1991) analytical stream function to model the mean Gulf Stream. Turbulent Lagrangian trajectories of passively advected particles were then calculated. In order to analyze particle tracks, the Gulf Stream region was divided into three areas (states)-

a southern gyre, a jet and a northern gyre. A symbolic sequence was formed, using the exit time formalism (Abel *et al.*, 2000) that brackets the time spent in each state, from the sequence of the particles passing through the states. The symbolic sequence was filtered to separate the two inherent time scales -slow and fast- of the system. A random traveler description of the particle tracks was derived for each of the filtered sequences of exit times and states. The sequence is shown to be of Markovian order one and constitutes a hierarchy of Markovian processes, one level for each of the two time scales. By means of entropic analysis it is clearly evident that this hierarchical model with a first order Markovian model for each time scale is sufficient to describe the dynamics of the advected particle.

7 Lagrangian predictability and assimilation of Lagrangian data

Lagrangian predictability is of great importance for practical applications such as search and rescue operations and dispersal of pollutants. The prediction of Lagrangian trajectories is an extremely difficult problem because of the inherent chaotic nature of nonlinear advection and because of our limited knowledge of the ocean velocity field. Various approaches to this problem are now being formulated. Recent simulations by Özgökmen *et al.* (2000; 2001) and Castellari *et al.* (2001) showed that accurate predictions, one week forecast errors $< 15\ km$, are possible if enough contemporary Lagrangian data are available for assimilation. Predictive skills increase using a simplified Kalman filter that assimilates Lagrangian data for Lagrangian prediction relative to estimates based on the movement of the center of mass of the data cluster or integrating climatological velocity fields. A normalized data density, DD, was defined as nd/md^2, where md is the mean diameter of the floats in the cluster and nd is the number of floats. For $DD > 1$ $drifter/degree^2$, only the Kalman-based filter assimilating Lagrangian data produced accurate estimates of near-surface buoy trajectories in the tropical Pacific.

A new improved Kalman filtering algorithm for Lagrangian prediction based on a consistent stochastic model for multi-particle Lagrangian motion in the upper ocean was formulated by Piterbarg (2001b) and is now being evaluated for the above mentioned buoys. The dependence of the Lyapunov exponent/predictability on parameters such as the Lagrangian correlation time and the Eulerian velocity space correlation radius has been investigated (Piterbarg, 2001a). A

general relation between Lagrangian stochastic models and Eulerian equations with stochastic forcing can be formulated and can be used, for example, for assimilating Lagrangian data into ocean circulation models written in the Eulerian form.

The prediction of constant level "balloon trajectories" in the atmosphere can be obtained by using an estimate of the Eulerian winds from the European Center for Medium-range Weather Forecasting (ECMWF) and a particle model with a simple linear Rayliegh friction that is proportional to the velocity (Dvorkin *et al.*, 2001). This approach was applied to balloons launched in Ecuador in the summer of 1998 by the French EQUATURE experiment. Best fits to observed EQUATURE trajectories yielded a one day relaxation time for the Rayleigh friction coefficient and that 85% of the position variability can be explained by advection by the winds. The 15% contribution from the particle model reduced the prediction error of balloon positions by 50%. Preliminary results of this technique applied to near-surface buoys in the tropical Pacific indicate a significant improvement, relative to advection by the climatological mean velocity field, in predicting Lagrangian trajectories.

Another outstanding research problem is how to best assimilate Lagrangian data into numerical circulation models. Lagrangian data are usually assimilated as moving Eulerian measurements. The Lagrangian nature of the data is usually not accounted for in data assimilation schemes. Work in progress by Chin used results from twin experiments where Lagrangian data was assimilated into a 4 layer, 20 *km* horizontal resolution wind-driven double-gyre experiment using MICOM, a reduced-order information filter (Chin *et al.*, 1999), and the assumption of treating the Lagrangian data as moving Eulerian data. Information from the velocity field was shown to improve predictions of both surface velocity and sea surface height. As a first step towards optimizing the Lagrangian information content of drifter data in data assimilation, trajectory position information was assimilated using the "snake" algorithm to minimize the distance between simulated float trajectories and "data" (float trajectories from the twin experiment) by correcting the model velocity field. The shape and strength of circulation features were improved.

Toner *et al.* (2001) presented results from model simulations of the Gulf of Mexico using the POM model and assimilating Lagrangian data by constraining the Geometrical Orthogonal Functions (GOFS) to match the Lagrangian velocities from drifters drogued at 50 *m*. The constrained GOFs-based reconstructed Eulerian velocity field improved forecasts of drifter trajectories by an order of magnitude in a 450 km^2 subdomain of the model with a Loop Current warm-core ring.

The development of an ocean circulation model formulated in Lagrangian coordinates would

lead to optimal assimilation of Lagrangian information contained in float trajectories. When assimilating Lagrangian data into regional primitive equation models, Lagrangian coordinates offer two distinct advantages since the float trajectories are the dependent state variables of the model. These advantages are (1) no model-data interpolation is needed and (2) simulations with open domains have well-posed forward and backward problems (Bennett and Chua, 1999; Mead and Bennett, 2001). The primary disadvantages are the highly nonlinear pressure gradient term and that viscosity can introduce spurious boundary layers. Their shallow-water model with Lagrangian coordinates was able to reproduce the eddy field, compared to a similarly forced traditional Eulerian circulation model in a doubly periodic domain for numerical simulations lasting a few months.

8   Concluding remarks

Important and complex research issues, discussed by working groups at the LAPCOD meeting, are

(1) What improvements in modeling, analysis, float design, and sampling are needed for coastal and biological applications?

(2) How to optimize the exchange of information between theoreticians and those collecting Lagrangian data? For example, what data are needed for better turbulence closure schemes, and what do numerical simulations of turbulence/stochastic models tell us about designing optimal Lagrangian-based sampling schemes for the ocean and coastal waters?

(3) How can the information from ARGO profiling floats be optimized for improving our understanding of ocean circulation and dynamics and for assimilating into ocean circulation models? How can we optimize the Lagrangian information content of floats for data assimilation?

More realistic models, new instrument and sensor designs, and high-resolution mapping of "index species" are especially needed to improve our understanding of the coastal/deep-water exchange processes. This will be especially challenging due to the small space scales and rapid time scales of both oceanic and atmospheric velocity fields, species patchiness and the fuzziness/complicated geometry of the coastal/deep water boundary as seen in ocean color and thermal observations. To achieve this goal will require a multi-disciplinary effort to improve atmospheric forcing fields for nested coastal models, to provide high resolution maps of bottom bathymetry, to launch smart "intelligent" floats with a suite of multi-spectral and chemical sensors, and to place

17

arrays of acoustic trackers to estimate biomass on all trophic levels from zooplankton to tuna. Smarter floats with better water-following properties will be needed to sample shelf exchange processes and shorelines with complicated geometries.

The primary recommendation for sampling design was to launch floats in clusters. More specifically, 3-4 floats seemed to be a good compromise between finite resources, regional coverage, and information on multi-particle statistics. On short time scales, this Lagrangian data can be used to estimate the parameters of one- and two-particle dispersion models, to estimate velocity gradients for dynamical balance (e.g., momentum, potential vorticity) studies and to constrain the velocity field of numerical simulations via data assimilation. Lagrangian data combined with high resolution surface velocity maps from radar imaging techniques enables one to test various parameterization schemes for vorticity dissipation.

Model-data comparisons of the near-surface velocity field were hampered by lack of data in divergent regions such as the Equatorial Pacific and the upwelling zones off west Africa. This would require a preferential deployment of floats in this area to ensure equal sampling density. Possible biases in dispersion statistics due to preferential deployment should be studied. Climatological data sets for model-data comparisons are available (*e.g.*, www.aoml.noaa.gov/phod/dac/dacdata.html, wfdac.whoi.edu). However, data for real-time forecasting of sea surface velocity is not readily available but should be in the near future.

The optimization of information from the planned large array of profiling floats in the ocean is an extremely timely and daunting task. Profiling floats are providing a wealth of hydrographic data, including data in historically data-void regions of the world ocean. This data will definitely increase our confidence in the time-averaged dynamic height maps and the resulting relative velocity fields, and it will constrain the thermohaline variables in numerical models. This constraint is important given our sparse and noisy estimates of surface fluxes of heat and salt. However, the position and velocity data at their deep travel depth of 1000 - 2000 m from this large data set will require new algorithms for real-time operational data assimilation. Except in strong current regimes, the present sampling of 2 positions every 7 to 14 days may lead to velocity estimates dominated by energetic eddies since the present sampling rate for position data for profiling floats is the same order as the eddy time scales. The use of these velocity estimates in present operational data assimilation methods that treat Lagrangian data as moving Eulerian measurements may lead to biases unless new techniques that take into account both the integrating aspect of Lagrangian measurements and the highly nonlinear relationship between Eulerian and Lagrangian

velocities are developed or a truly Lagrangian-based ocean circulation model is used. Regions of strong vertical velocity shears can introduce errors as large as 50% in estimating the deep absolute reference velocity. It is recommended that the next generation of profiling floats should be tracked so that position and velocity data can be generated over the entire 7-14 day period. Of course, such tracking will require greater resources that may reduce the number of floats or their geographical extent, so extensive numerical simulations should be conducted to optimize limited resources. The planned large array of profiling floats should be launched in clusters since they will disperse to the planned horizontal resolution of one float per five degree within a month or so after launch, and clusters would provide a wealth of data for stochastic models and Lagrangian predictability studies.

References

Abel, M., L. Biferale, M. Cencini, M. Falcioni, D. Vergni, and A. Vulpiani, 2000. Exit-time approach to $\epsilon - entropy$. *Phys. Rev. Lett.*, **84** (26), 6002-6005.

Abel, M., K.H. Andersen, G. Lacorata, A. Vulpiani, 2001. Hierarchical Markovian modelling of systems with several time scales, *Submitted, Physica D.*

Babiano, A., A. Provenzale. and A. Vulpiani (eds.), 1994. Chaotic Advection, Tracer Dynamics, and Turbulent Dispersion. Proceedings of the NATO Advanced Research Workshop and EGS Tropical Workshop on Chaotic Advection, Conference Centre Sereno di Gavo, Italy, 24-28 May 1993. Physica D76, 1-329.

Bauer, S., M. Swenson, A. Griffa, A.J. Mariano, and K. Owens, 1998. Eddy-Mean flow Decomposition and Edd-Diffusivity Estimates in the Tropical Pacific Ocean. *J. geophysical Research*, **103(C13)**, 30,855-30,871.

Bennett, A.F., and B.S. Chua, 1999. Open Boundary Conditions for Lagrangian Geophysical Fluid Dynamics. *J. of Computational Physics*, **153**, 418-436.

Berloff, P., J. McWilliams, and A. Bracco, 2001. Material transport in oceanic gyres. Part I: Phenomenology. *J. Phys. Oceanogr.*, in press.

Berloff, P., and J. McWilliams, 2001. Material transport in oceanic gyres. Part II: Hierarchy of Stochastic Models. *J. Phys. Oceanogr.*, in press.

Bezerra, M.O., M. Diez, C. Medeiros, A. Rodriguez, E. Bahia, A. Sanchez-Arcilla and J.M. Redondo, 1998. Study on the influence of waves on coastal diffusion using image analysis. *Applied Scientific Research.* **59**, 127-142.

Boffetta, G., M. Cencini, S. Espa, and G. Querzoli, 1999. Experimental evidence of chaotic advection in a convective flow. *Europhys. Lett.*, **48/6**, 629-633.

Boffetta, G., M. Cencini, S. Espa, and G. Querzoli, 2000. Chaotic advection and relative dispersion in an experimental convective flow. *Amer. Inst. of Physics*, **12/12**, 3160-3167.

Bower, A.S., N. Serra and I. Ambar, 2001. Spreading of Mediterranean Water around the Iberian Peninsula. *Journal of Geophysical Research*, accepted.

Bower, A. S., 1991. A simple kinematic mechanism for mixing fluid parcels across a meandering jet. *J. Phys. Oceanogr.*, **21**, 173-180.

Bracco, A., J.C. McWilliams, G. Murante, A. Provenzale, and J.B. Weiss, 2000a. Revisiting freely decaying two-dimensional turbulence at millennial resolution. *Amer. Inst. of Physics,* **12/11**, 2931-2941.

Bracco, A., J. LaCasce, C. Pasquero, and A. Provenzale, 2000b. The velocity distribution of barotropic turbulence. *Amer. Inst. of Physics,* **12/10**, 2478-2488.

Bracco, A., A. Provenzale, and I. Scheuring, 2000c. Mesoscale vortices and the paradox of the plankton. *Proc. R. Soc. Lond. B,* **267**, 1795-1800.

Castellari, S., A. Griffa, T.M. Özgökmen and P.-M. Poulain, 2001: Prediction of particle trajectories in the Adriatic Sea using Lagrangian data assimilation. *J. Mar. Sys.,* **29/1-4**, 33-50.

Coulliette, C., B.L. Lipphardt, Jr., S. Wiggins, C.E. Grosch, A.D. Kirwan, Jr., J.W. Hatfield, and J.D. Paduan, 2001. Advective Transport Near the Coast from High Frequency Radar: A Dynamical Systems Perspective. 1-11. (preprint)

Coulliette, C., and S. Wiggins, 2000. Intergyre Transport in a Wind-Driven, Quasigeostrophic Double Gyre: An Application of Lobe Dynamics. *Nonlinear Processes in Geophysics,* **7**, 59-85.

Cowen, R.K., K.M.M. Lwiza, S. Sponaugle, C.B. Paris, and D.B. Olson, 2000. Connectivity of marine populations: Open or closed? *Science,* **287**, 857-859.

Davis, R.E., 1991. Observing the general circulation with floats. *Deep Sea Res.,* **38**, S531-S571.

Dvorkin, Y., N. Paldor, and C. Basdevant, 2001. Reconstructing balloon trajectories in the tropical stratosphere with a hybrid model using analyzed fields. *Q.J.R. Meteorol. Soc.,* **127**, 975-988.

Falco P., A. Griffa, P.M. Poulain, E. Zambianchi, 2000. Transport properties in the Adriatic Sea as deduced from drifter data. *J. Phys. Oceanogr.,* **30**(8), 2055-2071.

Garfield, N., M.E. Maltrud, C.A. Collins, T.A. Rago and R.G. Paquette, 2001) Lagrangian flow in the California Undercurrent, an Observation and Model Comparison. *J. of Mar. Sys.,* **29** 1-4, 201-220.

Garraffo, Z., A. J. Mariano, A. Griffa, C. Veneziani, and E.P. Chassignet, 2001. Lagrangian data in a high resolution model simulation of the North Atlantic. I: Comparison with *in-situ* drifter data. *J. of Mar. Sys.,* 291-4,157-176.

Garraffo, Z., A. Griffa, A. J. Mariano, and E.P. Chassignet, 2001. Lagrangian data in a high resolution model simulation of the North Atlantic. II: On the Pseudo-Eulerian averaging of Lagrangian data, *J. of Mar. Sys.*, **29**1-4, 177-200.

Griffa, A., 1996. Applications of stochastic particle models to oceanographic problems. in *Stochastic Modelling in Physical Oceanography*, (Adler, Muller and Rozovskii, eds.), Birkhauser, Boston, 114-140.

Haller, G., 2000. Finding finite-time invariant manifolds in two-dimensional velocity fields, *CHAOS*, **10**, 99-108.

Haller, G. and Poje, A. 1998. Finite time transport in aperiodic flows. *Physica D*, **119**(3-4), 352-380.

Hitchcock, G.L., W.L. Wiseman, Jr., W.C. Boicourt, A.J. Mariano, N. Walker, T. Nelsen and E.H. Ryan, 1997. Property fields in the effluent plume of the Mississippi River. *J. of Mar. Sys.*, 12, 109-126.

Ide, K., F. Lekien, S. Wiggins, 2001. Distinguished Hyperbolic Trajectories in Time Dependent Fluid Flows: Analytical and Computational Approach for Velocity Fields Defined as Data Sets. 1-47. preprint

Kuznetsov, L., M. Toner, A.D. Kirwan, Jr., C.K.R.T. Jones , L. Kantha, and J. Choi, 2001. The Loop Current and adjacent rings delineated by Lagrangian analysis. *submitted, J. Mar. Res.*.

Lipphardt, B.L., A.D. Kirwan Jr., C.E. Grosch, J.K. Lewis and J.D. Paduan, 2000. Blending HF radar and model velocities in Monterrey Bay through normal mode analysis. *J. Geophys. Res.*, **105**, 3425-3450.

Longhetto, A., L. Montabone, A. Provenzale, H. Didelle, C. Giraud, D. Bertoni, R. Forza, 2001. Coherent vortices in rotating flows: a laboratory view, *submitted, Nuovo Cimento C.*

Malhotra, N. and S. Wiggins, 1998. Geometric Structures, Lobe Dynamics, and Lagrangian Transport in Flows with Aperiodic Time Dependence, with Applications to Rossby Wave Flow. *Journal of Nonlinear Science*, 8, 401-456.

Mariano, A.J. and H.T. Rossby, 1989. The Lagrangian Potential Vorticity Balance during POLYMODE, *J. Phys. Oceanogr.*, **19**(7), 927-939.

Maurizi, A., and F. Tampieri, 1999. Velocity probability density functions in Lagrangian dispersion models for inhomogeneous turbulence. *Atmos. Envi.*, **33**, 281-289.

Maurizi, A., and S. Lorenzani, 2000. On The Influence of the Eulerian Velocity PDF Closure on the Eddy Diffusion Coefficient. *Boundary-Layer Meteorology*, **95**, 427-436.

McClean, J.L., P-M. Poulain, J.W. Pelton and W.E. Maltrud, 2001. Eulerian and Lagrangian Statistics from Surface Drifters and two POP models in the N. Atlantic. *J. Physic. Oceanogr.*, submitted (also see http://po.gso.uri.edu/wbc/Mcclean/index.html)

McWilliams, J.C., 1984. The emergence of isolated coherent vortices in turbulent flow. *J. Fluid Mech.*, **146**, 21 - 43.

Mead, J.L. and A.F. Bennett, 2001. Towards regional assimilation of Lagrangian data: The Lagrangian form of the shallow-water model and its inverse. *J. of Mar. Sys.*, **291**-4, 365-384.

Miller, P.D., C.K.R.T.J. Jones, A. Rogerson and L.J. Pratt, 1997. Quantifying transport in numerically generated velocity fields. *Physica d.* **110**, 105-122.

Özgökmen, T.M., A. Griffa, A.J. Mariano, and L.I. Piterbarg, 2000. On the predictability of Lagrangian trajectories in the ocean. *J. Atmos. Ocean. Tech.*, **17/3**, 366-383.

Özgökmen, T.M., L.I. Piterbarg, A.J. Mariano and E. Ryan, 2001. Predictability of drifter trajectories in the tropical Pacific Ocean. *J. Physical Oceanography*, **31**, 2691-2720.

Pasquero, C., A. Provenzale, and A. Babiano, 2001. Parameterization of dispersion in two-dimensional turbulence. *under consideration for publication in J. Fluid Mech.*, 1-30.

Peters, H., L.K. Shay, A.J. Mariano and T.M. Cook. Current variability on a narrow shelf with large ambient vorticity *In press, J. Geophys. Res.*

Piterbarg, L.I., 2001a. The top Lyapunov exponent for a stochastic flow, modeling the upper ocean turbulence. *SIAM J.Appl.Math.*, accepted.

Piterbarg, L.I., 2001b. Short-term prediction of Lagrangian trajectories. *J.Atm. Ocean. Techn.*, **18**, 1398-1410.

Polivina, J.J., P. Klieber, and D. R. Kobayashi, 1999. Application of TOPEX-POSEIDON satellite altimetry to simulate transport dynamics of larvae of spiny lobster, Panilurus marginatus, in the Northwestern Hawaiian Islands, 1993-1996. *Fish. Bull.*, **97**,132-143.

Poulain, P.-M., 1999. Drifter Observations of surface circulation in the Adriatic Sea between December 1994 and March 1996. *J. of Mar. Sys.*, **20**, 231-253.

Poulain, P.-M., 2001. Adriatic Sea surface circulation as derived from drifter data between 1990 and 1999. *J. of Mar. Sys.*, **29**, 3-32.

Rolinski, S. and J. Suendermann, 2001a. Description of the suspended particulate matter phytobenthos reaction model, Tech. Rep. MAS3 - CT97-0145 F-ECTS-REL-T043.

Rolinski, S. and J. Suendermann, 2001b. Modelling the dynamics of suspended particulate matter and phytobenthos - Report on the application to Venice Lagoon, Tech. Rep. MAS3 - CT97-0145 F-ECTS-REL-T049.

Rossby, H.T., S.C. Riser, and A.J. Mariano, 1983. The Western North Atlantic - A Lagrangian Viewpoint. In: *Eddies in Marine Science*, A.R. Robinson, Ed., Springer-Verlag, 1983, pp. 66-91.

Sabatis A., Salat J. and Olivar M.P., 2001. Advection of continental water as an export mechanism for anchovy, Engraulis encrasicolus, larvae. In: An interdisciplinary view of the Ocean, J.L. Pelegrm, I. Alonso and J. Arstegui (eds.). *Scientia Marina*, **65** (suppl. 1), 77-87.

Shay, L.K., T.M. Cook, B.K. Haus, J. Martinez, H. Peters, A.J. Mariano, J. VanLeer, S.M. Smith, P.E. An, A. Soloview, R. Weisberg, and M. Luther, 2000. A submesoscale vortex detected by very high resolution radar, *EOS*, **81**.

Taylor, G.I., 1921. Diffusion by continuous movements. *Proc. London Math. Soc.*, **20**, 196-212.

Thompson, D.J., 1986. A random walk model of dispersion in turbulent flows and its application to dispersion in a valley. *Quat. J.R. Met. Soc.*, **112**, 511-529.

Thompson, D.J., 1987. Criteria for the selection of stochastic models of particle trajectories in turbulent flow. *J. Fluid Mech.*, **180**, 529-556.

Toner, M., A.D. Kirwan, Jr., L. Kantha, J. Choi, 2001. Can general circulation models be assessed and and their output enhanced with drifter data? *J. Geophysical Research*, **106**, 19,563-19,579.

Weis, J.B. and J.C. McWilliams, 1993. Temporal scaling behavior of decaying two-dimensional turbulence. *Phys. Fluids A.*, **5**, 608-?.

Wiggins, S., 1992. *Chaotic Transport in Dynamical Systems*. Springer-Verlag: New York.

Wilson, W.D. and K.D. Leaman, 2001. Transport pathways through the Caribbean: The tropical origins of the Gulf Stream, *J. Mar. Ed.*, **16**(1), 14-17.

Wolanski E., Doherty P., and Carleton J. 1997. Directional swimming of fish larvae determines connectivity of fish populations on the Great Barrier Reef. *Naturwissenschaften*, **84**, (6), 262-268.

Ye, J. and R. W. Garvine. 1998. A model study of estuary and shelf tidally driven circulation. *Cont. Shelf Res.*, **18**, 1125-1155.

Zhang, H.M., M.D. Prater, and T. Rossby, 2001. Isopycnal Lagrangian statistics from the North Atlantic Current RAFOS float observations. *J. Geophysical Research*, **106** (C7), 13817-13836.
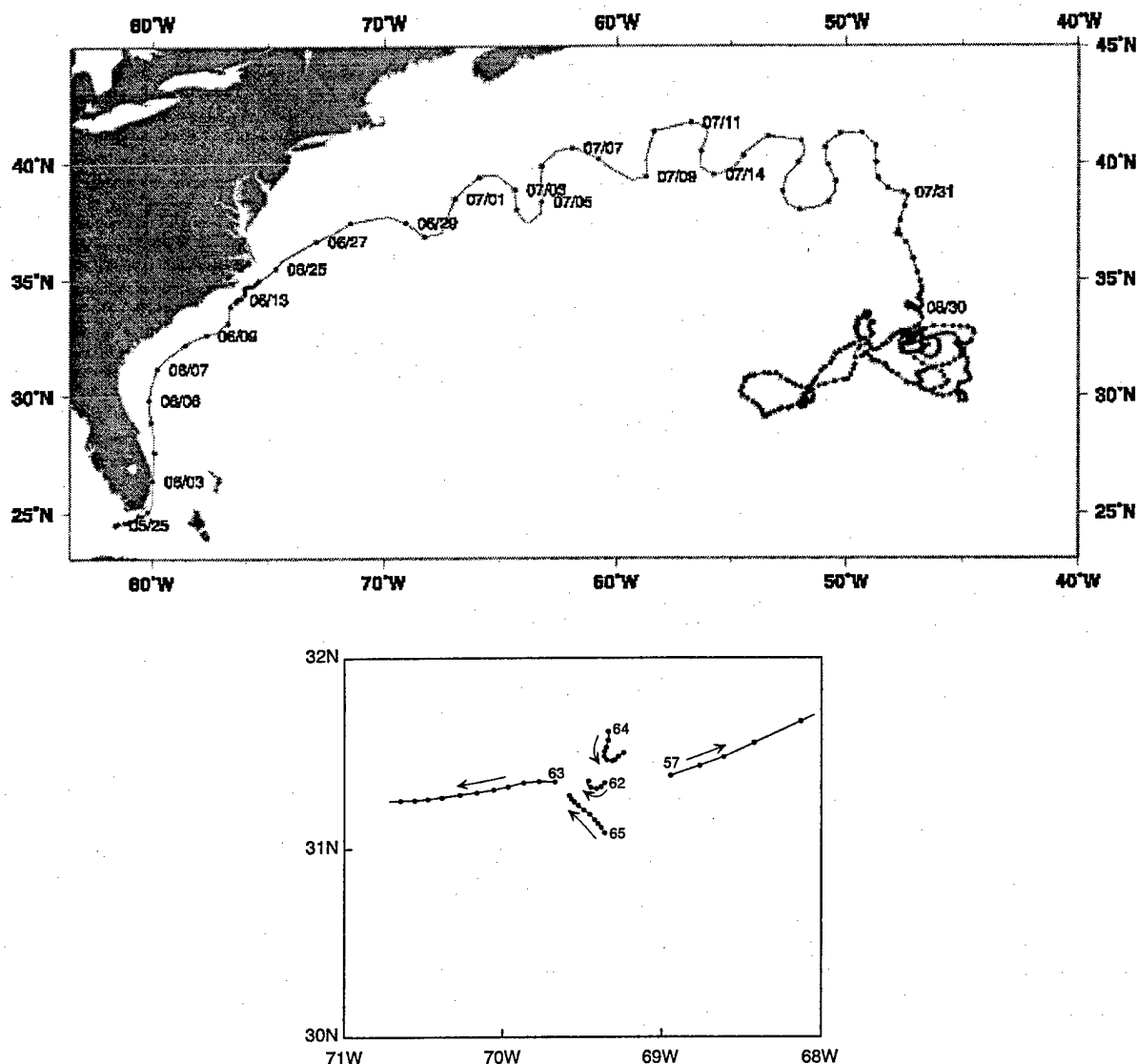
Figure 1: (a) The trajectory of a holey-sock drifter drogued at 10 m depth. Launched off of the Florida Keys (05/25) by Tom Lee, the drifter is entrained by the Florida Current, its path is deflected by the Charleston Bump (06/09), and it meanders in the Gulf Stream (06/29-07/29). After leaving the stream east of 50°W, it exhibits eddy motion (08/30) and a slow drift to the south/west before its death thirteen months later in September of the next year. (b) These SOFAR floats trajectories, launched by Tom Rossby as part of the POLYMODE Local Dynamics Experiment at a depth of 700 m in June of 1978, are an early example of what a flow near a saddle point would look like. The position of the floats is given every day with an arrow indicating their initial displacement.
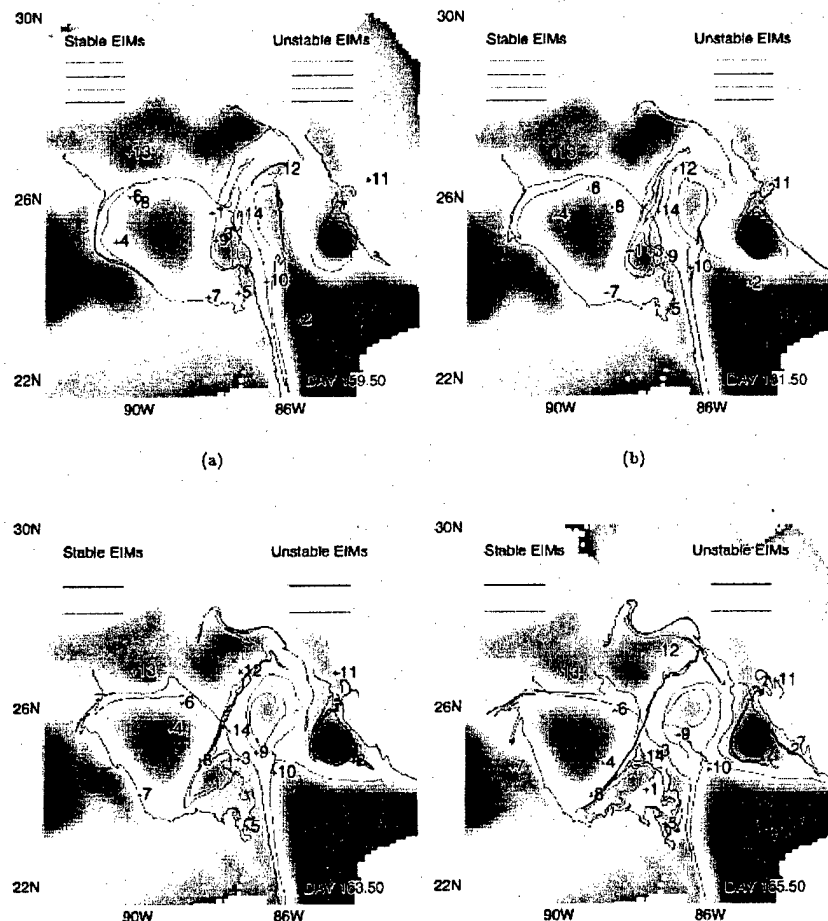
Figure 2: Effective Invariant Manifolds (EIMs) in the eastern Gulf of Mexico during June, 1998. The manifolds are computed from the 50 m horizontal velocity of a data (NOGAPS, MCSST, TOPEX/POSEIDON) driven University of Colorado Princeton Ocean Model (CUPOM) and are superimposed on the model height anomaly (green indicates positive and blue negative). The unstable EIMs (which grow in time) and the stable EIMs (which shrink in time) form the Lagrangian boundaries of coherent structures in the Eulerian velocity field. In the eastern Gulf, these structures are two anticyclones, two cyclones, and the Loop Current. Positions of fourteen drifters, deployed by Horizon Marine for Climatology And Simulation of Eddies (CASE) and the drogued at 50 m, are indicated by an asterisk (*). The data are shown every two days: a) A small cyclone is between a northward meander in the Loop Current to the east and a Loop Current ring to the west. A stationary Tortugas cyclone is to the east of the meander neck. The Meander neck is forming another Loop Current ring. b) The small cyclone travels south and begins to cleave the eastern edge of the large Loop Current ring. The meander neck narrows and recirculation begins in the new ring. c) The small cyclone cleaves about 15% of the Loop Current Ring. The separation of the meander into a new ring is more pronounced as the Lagrangian boundaries form. d) The small cyclone and the cleaved portion of the Loop Current ring merge. Interesting drifter pairs are 6,8; 5,7; and 2,10. Drifters 6 and 8 are near each other in a) and b), but in c) and d) drifter 8 follows the eastern boundary of the Loop Current ring while drifter 6 stalls near the stagnation point. Drifters 5 and 7 are near each other in a), but in b) drifter 5 is caught in the cleaved portion of the Loop Current ring while drifter 7 remains in the main portion. Drifters 2 and 10 in a) are on either side of the western boundary of the Loop Current. Drifter 2, inside the Loop Current, heads for the Tortugas cyclone b), and just misses the northern Loop Current boundary that is forming as the meander pinches c). Drifter 10, however, heads toward the stagnation point b), c) and does not cross the northern Loop Current boundary d).